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SPACE SHUTTLE MAIN ENGINE PROPELLANT PATH LEAK DETECTION USING SEQUENTIAL IMAGE PROCESSING

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ABSTRACT

Initial research using theoretical radiation transport models established that the occurrence of a leak in the powerhead of the SSME is accompanied by a sudden but sustained change in intensity in a given region of an image. During this work period, temporal processing of video images on a frame-by-frame basis has been used to detect leaks within a given field of view. The leak detection algorithm developed in this study consists of a digital highpass filter cascaded with a moving average filter. The absolute value of the output image is then averaged over the full frame to produce a single time-varying mean value estimate that is indicative of the intensity and extent of a leak. Four video sequences from an actual SSME test firing were analyzed using this technique. A hydrogen gas leak was detected approximately four seconds before existing sensors initiated shutdown during the test. The resulting plots of the full frame mean value versus time verify the effectiveness of the system. A detailed specification of the hardware and software required to implement the algorithm in real time was performed. The proposed system consists of a personal-computer-based system with commercially available add-in cards capable of digitizing and processing standard RS-170 format video signals at 30 frames per second.

I. INTRODUCTION

The rapid detection of propellant leaks from the Space Shuttle Main Engine (SSME) during test firing is crucial to the prevention of catastrophic failures. Ruptures of high-pressure lines and internal components due to thermal shock, mechanical stress, erosion, and material fatigue often result in failure modes with sufficiently long time constants to allow detection and safe shut down. Recent advances in imaging and image processing technology provide the hardware necessary for visual and infrared observation of these phenomena and the computing capability required for processing the signals and detecting the occurrence of a leak within the field of view. Thus, a system capable of detecting leaks from images acquired sequentially during test firing in real time is of value to the development of the SSME and is realizable with current technology. This study investigated this approach and established its feasibility and applicability to the program.

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Previous work in this area by Shohadaee and Crawford [1], [2] concentrated on establishing the feasibility of observing hot or cold leaks using infrared imaging. The theoretical models developed were used to predict radiation transport in absorbing, emitting and scattering media. These models predicted the intensity of both background and plume radiation reaching a sensor location, and they were used for designing validation experiments. The feasibility of infrared detection of leak plumes was demonstrated on subscale simulated plumes to determine sensitivity, signal-to-noise ratio, and general suitability. Both hot and cold leaks were readily detected as measurable intensity changes by the sensor.

However, to detect the occurrence of a leak, the temporal aspects of the process must be considered. The previous analysis showed that the occurrence of a leak should result in a sudden change in intensity in a given region of an image. Furthermore, the change should be sustained for a typical persistent leak. The time variation of the intensity at a point within the area of the leak should therefore be similar to that of a step function, although other smaller intensity variations are also present due to normal operating conditions. The problem becomes that of detecting a step function in the presence of additive noise.

The leak detection system presented here was designed to quickly and automatically detect a step-like change in intensity in a sequence of images [3], [4]. Temporal processing is carried out at each point in full-frame digitized video data. The system consists of a causal, recursive high-pass filter that removes slowly-varying background intensities cascaded with a moving average filter that accumulates transmitted sustained changes. The absolute value over the full output frame is averaged to produce a time-varying mean value indicative of the level and spatial extent of any leak.

The leak detection algorithm has been implemented on a general purpose digital image processor and successfully applied to actual test-stand firing data. Four video image sequences of a SSME test-stand firing were analyzed with this technique to evaluate its performance under actual firing conditions. A hydrogen leak was detected in three of the four camera views approximately 4 sec before existing sensors initiated an early shutdown.

In order to implement the algorithm in real-time with a standard 30 frames/sec video signal, a system with memory for approximately 16 previous frames and a processing throughput of 37 million operations/sec is required. A personal-computer-based system meeting these specifications has been designed with commercially-available add-in cards utilized where possible. Verification of timing requirements has been carried out with a software simulator to establish proper system operation.

The following section describes the leak detection algorithm and discusses some of the considerations for implementing it on digital image processing equipment. Section III discusses the processing of the four video sequences from a SSME test firing. Specifications for a real-time data acquisition and processing system implementing the algorithm are presented in Section IV. A summary and conclusions are given in Section V.

II. THE LEAK DETECTION

Time-varying intensity levels in video images are an inherently discrete signal with a sampling rate of 30 Hz for standard television format. Therefore, techniques of digital signal processing are directly applicable to the analysis. A detailed derivation of the step detection algorithm used in this study was given in [4] along with a numerical analysis of its performance. For completeness, a brief

description of it is presented here.

The processing algorithm developed for this application can be broken down into four component blocks. The first three blocks involve processes that are applied in parallel at each point (pixel location) in the image, while the fourth incorporates the spatial information over the entire field of view. In concept, the four steps can be described as follows:

1. A highpass filter is applied to remove the constant or slowly-varying background intensity while passing sudden changes.

2. A moving average filter accumulates any sustained changes transmitted through the highpass filter.

3. The absolute value of the output from the moving average is taken to allow for detection of positive or negative intensity changes.

4. The pixel values of the output image are summed or averaged over the field of view to produce a single time-varying quantity indicative of the extent and intensity of a leak.

For speed of response and simplicity of computation, the highpass filter has been chosen as a single-pole recursive filter with a z-domain transfer function given by

$$F(z) = \frac{1+\beta}{2} \frac{1-z^{-1}}{1-\beta z^{-1}} . \qquad (1)$$

The cutoff frequency of the filter is determined by choice of the pole value β.

The moving average filter has a transfer function

$$G(z) = \frac{1}{n} \sum_{k=0}^{N-1} z^{-k} = \frac{1}{n} \frac{1-z^{-N}}{1-z^{-1}} \qquad (2)$$

These two filtering operations can be combined into a single cascade connection with an effective transfer function given by

$$H(z) = F(z)\, G(z) = \frac{1+\beta}{2N} \frac{1-z^{-N}}{1-\beta z^{-1}} \qquad (3)$$

which corresponds to the difference equation

$$y(n) = \beta y(n-1) + \frac{1+\beta}{2N} [x(n) - x(n-N)] \quad (4)$$

Equation (4) is the difference equation defining the temporal filtering that is carried out at each point in the image. Processing is completed by taking the absolute value of the resulting signals at all pixel locations and averaging them over the full field of view.

While equation (4) conceptually describes the filtering process at each pixel location, the actual implementation consists of the recursive computation given by

$$y(n) = \beta y(n-1) + x(n) - x(n-N) . \qquad (5)$$

Multiplication by the gain factor $(1 + \beta)/2N$ is performed on the sum of the absolute values of the output pixels in conjunction with normalization to obtain the mean value. This substantially reduces computational requirements.

It has been shown [4] that the signal-to-noise ratio of the output signal can be maximized for a given value of β by choosing the number of terms in the moving average according to

$$N = -\frac{1.2564}{\ln \beta} \qquad (6)$$

This condition sets the memory requirements of the system in terms of previous input images that must be stored.

III. APPLICATION TO TEST STAND DATA

The system has been applied to visible wavelength image data acquired during an actual SSME test firing in which a premature shutdown occurred. Following the ignition sequence, the engine entered mainstage mode and operated normally for roughly 3.5 sec. At that time, hydrogen gas began to leak from the low pressure fuel turbopump (LPFTP). This leaked gas ignited intermittently, causing small flames about the powerhead for approximately 4 sec until a large flash fire was detected by an external sensor and the shutdown sequence was initiated.

Four image sequences of this test transcribed from film onto magnetic videotape were supplied by the National Aeronautics and Space Administration (NASA). These sequences correspond to four different views of the engine powerhead taken during the same test firing from data acquisition cameras which were denoted numbers 1, 6, 7, and 8 by NASA. Figure 1 shows the fields of view for each of these four camera positions. These images were acquired prior to ignition and therefore are clearer than those processed during the firing. The most prominent features in these photographs are the low pressure fuel turbopump (LPFTP) discharge duct (Fig. 1(a,d)) and the low pressure oxidizer turbopump (LPOTP) discharge duct (Fig. 1(b,c)). The LPFTP from which the leak occurred is barely visible in the upper right hand corner of Fig. 1(d) (camera position 8). (Because of the wide-angle lenses used on the cameras, features are somewhat distorted.) Figure 1(a) (camera position 1) shows the typical vapor clouds that are present during an engine test.

This image data was transferred to an optical disc recorder/player and processed frame-by-frame with the leak detection algorithm. Because of the large amount of noise in this data, it was found that values for β and N of 0.91 and 13, respectively, were required for processing. (Use of higher values was limited by the number of frame buffers available in the image processor.) Processing began just prior to ignition following a pre-test synchronization flash and concluded with the post-test mode. For each sequence, a plot of the output mean value (average intensity of the output image) versus frame number was computed and is shown in Figs. 2(a-d).

The peaks in the plots of Figs. 2(a-d) correspond to the events occurring during the engine test. The peaks detected during ignition were caused by lights being turned on and by the plume forming at the bottom of the nozzle. Ignition also caused the nozzle to vibrate which shook loose frost that had accumulated on various cold engine components. These events caused the first large peaks in the output mean plots. As the engine entered mainstage mode, the mean value output reduced to that caused by the noise.

The leak near the LPFTP resulted in a large peak in the output mean value at approximately 6.1 sec in Fig. 2(d) (camera position 8), and smaller, but still noticeable peaks at the same time in Figs. 2(a) and 2(b) (camera positions 1 and 6). While the leak was detected in three of the four sequences, it was most obvious from camera position 8. The leak caused a flow that purged the vapor clouds normally surrounding the powerhead and cleared the field of view. Flames are visible from 6.1 to 10.1 sec in camera position 6 data and resulted

in substantial output mean values during that time as shown in Fig. 2(b).

The flash fire at 10.1 sec is evident in all the plots of Fig. 2. It was detected by the monitoring systems presently in use and the shutdown sequence was initiated. The engine vibration and water spray associated with shutdown and post-test procedures also result in large peaks in the output mean value in all four plots of Fig. 2.

As the plots in Fig. 2 show, if this system had been implemented for this engine test, the leak/no leak decision would have probably been positive at approximately 6.1 sec. Thus, the engine would have begun shutdown 4.1 sec before the systems presently implemented indicated. This analysis of these four data sets thus demonstrates the potential value of this technique for monitoring SSME test firings.

IV. SYSTEM SPECIFICATIONS

The conceptual structure of the system required to implement the leak detection algorithm is shown in Fig. 3 along with a summary of the nominal system specifications. An A/D converter (or frame grabber) digitizes the input video voltage signal. This data is then transferred via an internal data bus to one or more high-speed digital signal processors where the bulk of the numerical computations is carried out. The resulting output sequence of mean values is then transferred to the host computer for display and archival storage.

The proposed system is intended for standard RS-170 format input video signals with a framing rate of 30 Hz and 480 lines/frame. Adequate resolution is achieved by digitizing each line into 512 samples. The dynamic range of the intensity values can be covered with 8 bits (1 byte) per pixel. If this A/D conversion operation is carried out in a dedicated frame grabber and data transferred to other processing hardware, the continuous transfer rate of the internal data bus is nominally 7.4 Mbytes/sec.

Examination of equation (5) shows that at each pixel, 3 arithmetic operations -- 1 multiply and 2 adds -- are required for the filtering process. Also, the absolute value constitutes one operation/pixel, and the sum over the field of view requires one operation/pixel. For a 480 × 512 image pixel array and a 30 Hz framing rate, the necessary effective processing speed is thus roughly 37 million operations/sec.

Memory requirements for the processors are governed by the number of terms in the moving average N, which is determined by the criterion given in equation (6). Practical experience with SSME test stand data has shown that up to 15 previous input frames in addition to the present can be required for proper performance. One additional frame is needed for the previous output frame. While input frames can be stored in 1 byte/pixel integer format, the output frame must be in 4 byte/pixel floating-point format. The total memory required is thus 5 Mbyte of access memory.

This system design is intended to compute the sum of the absolute values of the outputs defined by (5), normalize by the appropriate scale factor $((1 + \beta)/(2N \times 480 \times 512))$, and transfer those values to the host computer via its internal bus at the framing rate of 30 Hz. This produces the final mean value at discrete time intervals. This value will be written to disk for archival storage. In addition, the value can be compared with a threshold value during processing to determine whether the "red line" condition has been exceeded indicating a leak has occurred. Another feature is that a manual override from the keyboard must be

provided to prevent false alarms from occurring during the ignition sequence and other planned anomalous events.

Figure 4 is a block diagram of the recommended system. An overlay frame grabber (OFG) from Imaging Technology, Inc. was selected for the video digitizing function because of its ability to continuously output all frames of digitized video data over a standard synchronous digital data bus -- the VISIONbus. The VISIONbus data is split into four separate streams, each of which is routed to a separate Texas Instruments TMS320C40 32-bit floating-point digital signal processor using a custom-built interface board which sends either every fourth pixel or every fourth row of pixels to the same processor. This interface is the only custom-built component in the system and can be fabricated on a single PC-plug-in card with four synchronous first-in first-out memories (FIFOs) and five state machines. The four C40 processors are located on two Spirit-40 AT/ISA dual-C40 PC-plug-in boards from Sonitech International, Inc.

A C40 assembly language program was written to verify that the C40 processors can perform the processing of (5) in the time available. This program carries out the calculations of (5), takes the absolute value of the pixels computed from (5), and sums these absolute values. The program was run on a C40 simulator and was optimized to minimize the processing time required per pixel. With appropriate local and global bus memory, and 40 MHz C40 processors, the program requires 9 instruction cycles of 50 nsec each to process one pixel giving a total processing time of 450 nsec/pixel. Although pixels become available on the VISIONbus at an average rate of one every 136 nsec, each of the four C40 processors only receives a new pixel every 544 nsec. Thus, the 450 nsec/pixel processing time is sufficient to guarantee that incoming video data can be continuously processed. Sufficient memory is available in this system for storing the image currently being processed and 15 past images. Therefore, a value as large as $N = 15$ can be used in (5).

V. CONCLUSIONS

A method for detecting abrupt, step-like changes in a time sequence of images has been developed, implemented on general-purpose equipment, and tested. The detection algorithm functions by filtering the input data with a cascade connection of a highpass filter and a moving average. The absolute value of the resulting image is then averaged over the field of view to determine a mean value estimate. This time-varying value can then be compared to a pre-set threshold to determine a "red-line" condition for shutdown.

This method has been applied to actual video data acquired during a SSME test firing. The analysis of the test-stand data indicates the applicability of this technique to actual SSME test firings and its ability to identify anomalous events.

A system has been identified and specified for real-time on-line implementation of this method for SSME leak detection. This system uses an IBM compatible personal computer as a host platform and an Imaging Technology Overlay Frame Grabber with the VISIONbus for data acquisition and transfer. Processing is carried out by four TMS320C40 processors located on two Sonitech Spirit-40 add-in cards and requires that a custom interface be fabricated to transfer data from the frame grabber to the processors. The processing algorithm has been programmed and proper timing to achieve the required effective throughput rate has been verified.

Future work in this effort includes examining the effectiveness of the algorithm in infrared imaging applications and other test stand data sequences. Work is also planned to extend this technique to color image processing to detect sudden changes in plume color that otherwise may not result in detectable intensity variations. Finally, application to actual launch-pad data is also a possibility.

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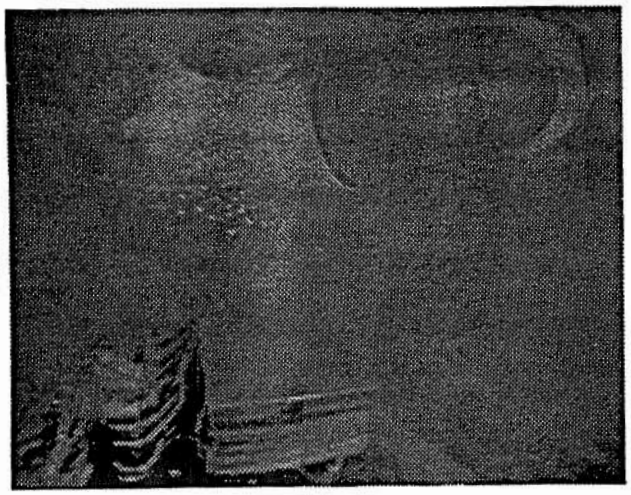
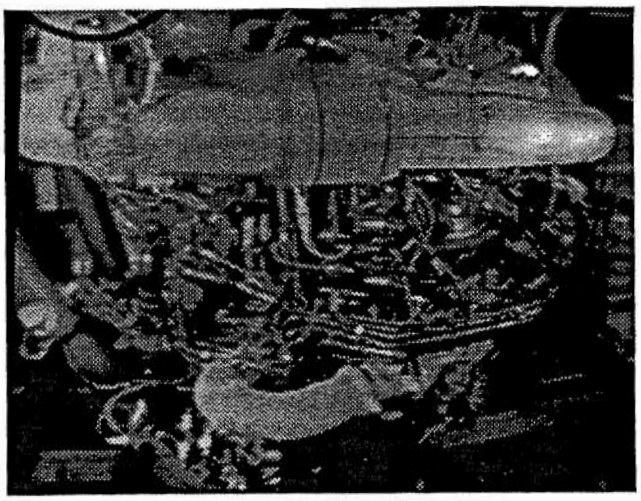


(a)



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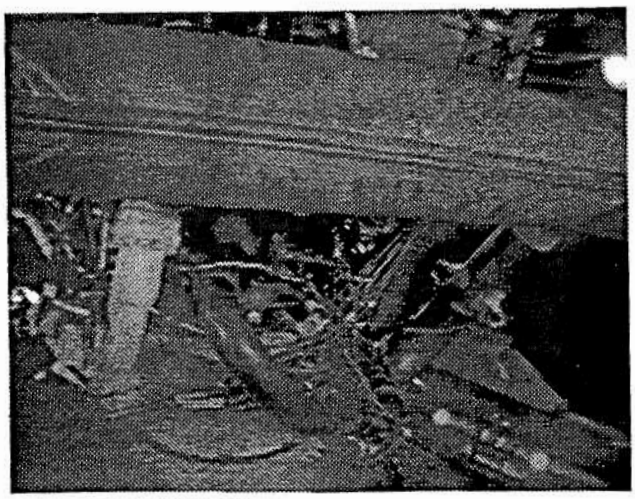

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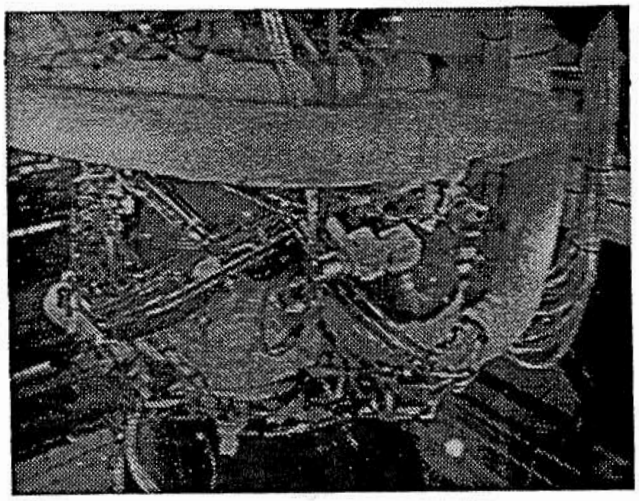

(d)

Figure 1. Fields of view for each of the four cameras: (a) position 1, (b) position 6, (c) position 7, (d) position 8.

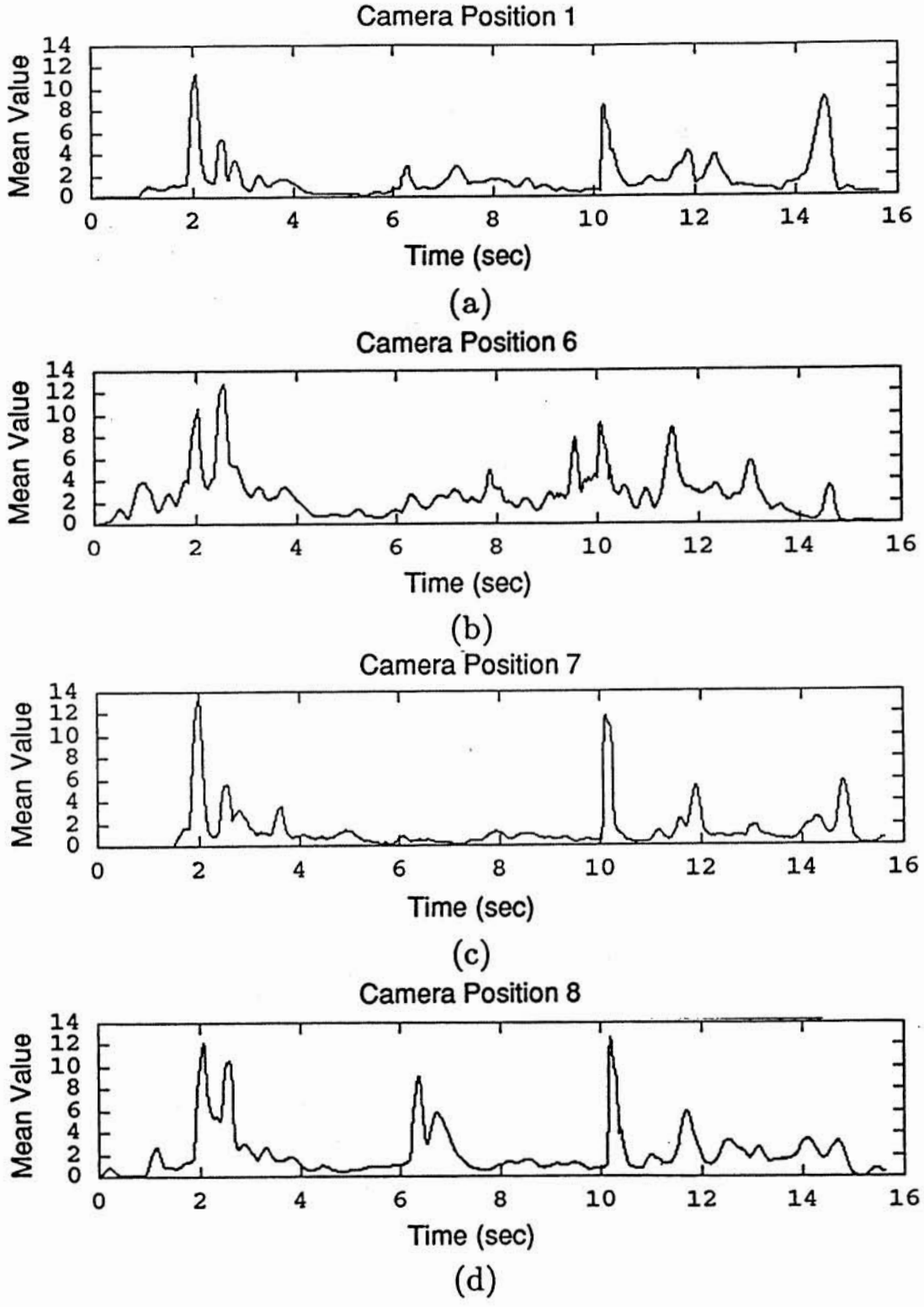

Figure 2. Mean value of output images versus time for test-stand video data. Note the detection of the leak near 6.1 sec. (Some initial data from camera position 7 (c) was missing, so output was set to zero in that range.)

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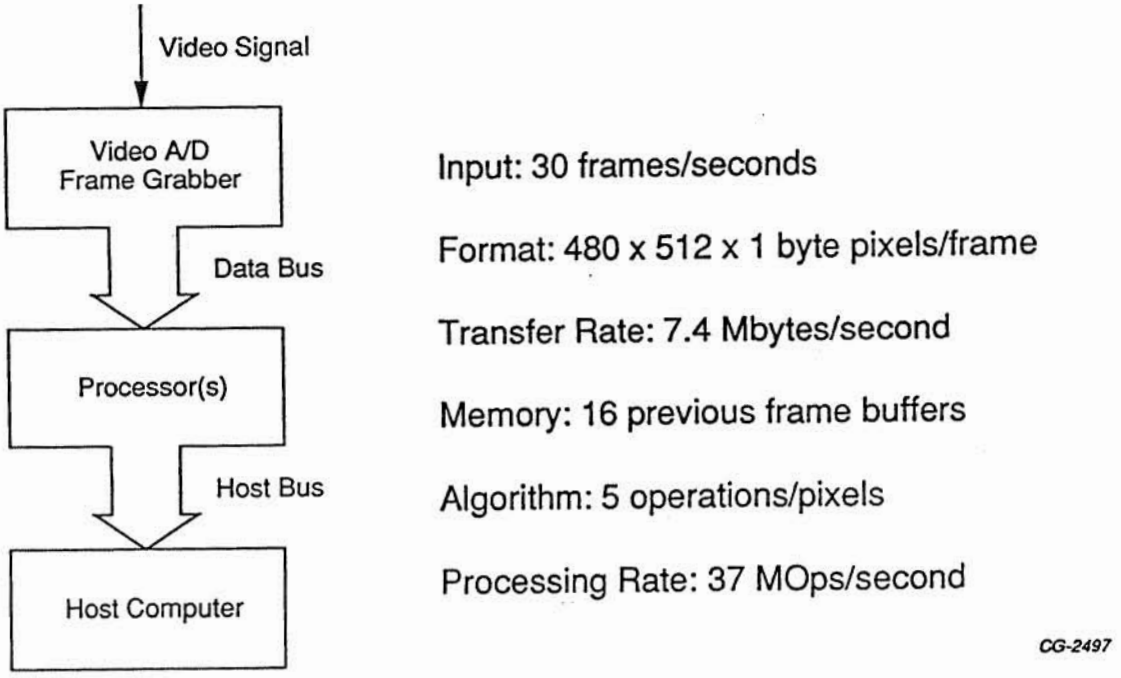

Figure 3. Basic system configuration and nominal specifications.

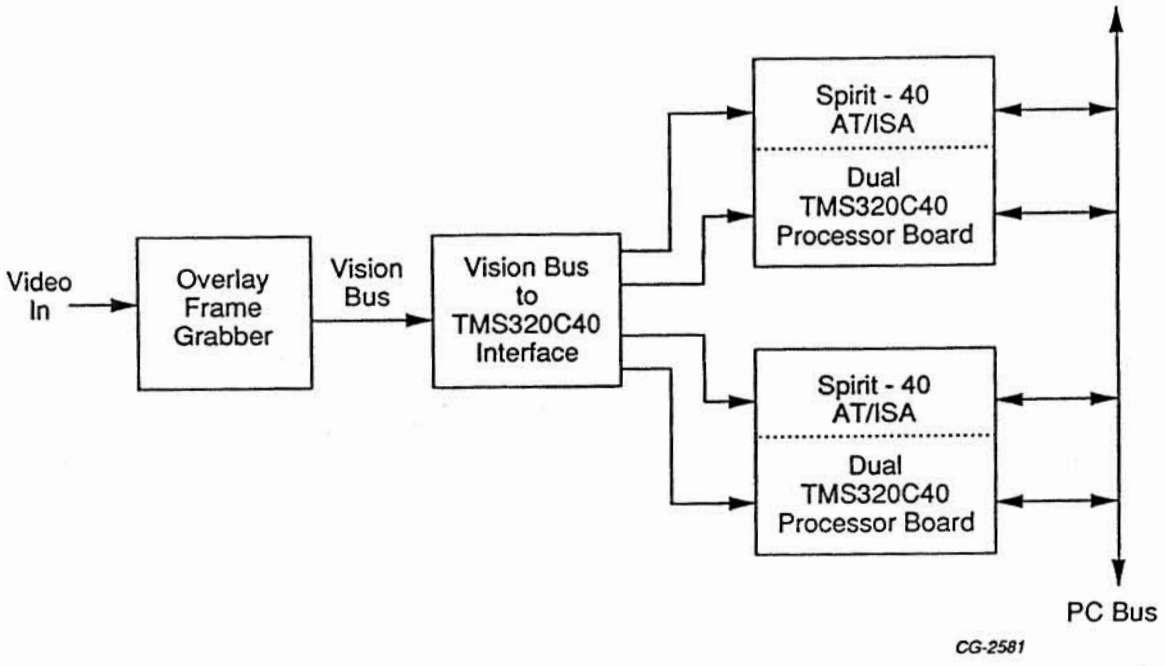

Figure 4. Block diagram of recommended system using TMS320C40 processors.

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